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PROTONS AND HELIUM NUCLEI WITHIN INTERPLANETARY MAGNETIC

REGIONS WHICH CO-ROTATE WITH THE SUN

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# Protons and Helium Nuclei Within Interplanetary Magnetic

## Regions Which Co-rotate with the Sun

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Abstract. From IMP-I measurements we showed in 1964 that fluxes of protons of  $> 1$  Mev energy appeared for several days in a sequence of six consecutive 27-day intervals. We concluded that these protons were confined within a region co-rotating with the sun which modulates the galactic cosmic radiation at the orbit of Earth with the same 27-day recurrence period. This region has persisted for more than 20 solar rotations and was observed with the IMP-I magnetometer by Ness and Wilcox to possess special characteristics.

The energy spectrum of the protons in the leading and trailing sides of the co-rotating region was measured. A helium component continuously associated with the protons has been found with an energy spectrum of the form  $\propto E^{-2}$  Mev/nucleon in the energy range 2 to 30 Mev/nucleon. Evidence from the OGO-I satellite indicates that the proton and helium fluxes are not only present within co-rotating regions, but are also present at lower intensity and with different spectra at all times throughout a 2.5 month period. The source for continual acceleration of these protons and helium nuclei is discussed.

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## I. Introduction

Proton fluxes in the Mev energy range were detected with Explorer XII by Bryant, et al. (1963) approximately 27 days after a solar flare proton event. From this they concluded that the protons were the residue of the earlier flare event, and were associated with a solar M-region. We later found (Fan, Gloeckler and Simpson 1964) enhanced proton fluxes in interplanetary space in the energy range 1 to 20 Mev which persisted in a recurring series of four solar rotations (and now extended to six rotations as shown in Figure 1) in 1963 and 1964 without any evidence for solar flares. Since this recurring region also was correlated with the 27-day intensity modulation of primary cosmic rays, we pointed out that it must be a recurring magnetic region within which these protons were confined. Neutron monitor intensity variations,  $K_p$  changes and a solar unipolar magnetic region displayed a similar 27-day correlation in the previous solar cycle (Simpson, Babcock and Babcock, 1955). The series associated with Figure 1 was traceable through neutron monitor intensity variations for over 20 solar rotations (Mori, Ueno, Nagashima and Sagisaka, 1964). We concluded from these preliminary results that there may be persistent acceleration of these protons either at the sun, or in the 27-day recurring magnetic region in interplanetary space.

Recently, Bryant et al. (1965) have found a series of six additional recurring proton fluxes earlier in 1963 which is part of the same

long-lived, recurring region we reported for our IMP-I observations. They note that the energy spectra of successive recurrences are similar and that there is no evidence of their origin in solar flares. Their results add further evidence that the protons are continually accelerated.

In this paper we (1) discuss the main characteristics of the proton intensity distributions and energy spectra, (2) introduce evidence for a helium component associated with the protons in the co-rotating region, and (3) conclude from measurements in late 1964 that the proton and helium fluxes were continuously present at lower intensity and with different spectra, for all times studied throughout a period of two and a half months.

## II: Proton Fluxes and Spectra

In addition to the main recurring series of proton intensity increases shown below A in the left portion of Figure 1, there is a second intermittent, series below B beginning on day 064. (A description of the IMP-I instrument has been published (Fan, Gloeckler, and Simpson 1965).) Direct evidence is now available to show that the interplanetary magnetic field as measured on IMP-I reverses direction and increases in intensity near the time of appearance of the proton increases (private exchange of information between N. Ness and J. A. Simpson, November 1964). Ness and Wilcox (1965) find that regions of high magnetic field intensity follow these co-rotating field reversals. We note that not all field reversing, co-rotating regions contain protons at all times.

There is significant structure in the proton intensity distribution persisting for more than one solar rotation, as shown in Figure 1. This suggests that the proton intensity variations during a 27-day recurrence are spatial and arise from longitudinal variations of interplanetary magnetic field intensity. This spatial structure in the magnetic field may be carried into interplanetary space by the solar wind. If so, these magnetic channels would connect with the Sun over local regions of intense magnetic field and enhanced coronal heating, since the solar wind has been observed to have a higher than average velocity and particle density at these times (Lyon, Bridge, Egidi and Rossi 1964).

The differential energy spectrum for all these proton 27-day events are similar and may be fitted to a power spectrum in kinetic energy  $E$  of the form  $E^{-\gamma}$ . If we divide the event for days 336 - 344 in Figure 1 into two time periods we obtain the spectra shown in Figure 2. The spectrum in the leading region of the co-rotating field seems to be flatter than for the trailing region.

### III. Evidence for Helium Component

The spectra of helium from the galaxy have been investigated above 7 Mev/nucleon on the IMP-I and IMP-II satellites where we found evidence that the slopes of the helium spectra undergo a change of sign near 20 Mev/nucleon, indicating the presence of an additional spectrum of helium at lower energies, from 27-day recurring intensity increases (Fan, Gloeckler

and Simpson, 1965, this conference). A particle telescope of different design was carried on the OGO-I satellite to analyze these proton and helium spectra down to 1 Mev/nucleon. The telescope is composed of two solid-state detectors and an absorber within a scintillator anticoincidence cup arranged as shown in the insert of Figure 3. This telescope arrangement makes it possible to analyze particles in the energy range 1 to 35 Mev/nucleon in the presence of background cosmic radiation. Although the amplitude of 27-day recurrences became very small late in 1964 at solar minimum activity, we have identified a series including 18 - 19 October 1964. This period was confirmed by neutron monitor intensity changes and by the increase in the  $> 1$  Mev protons in the IMP-II satellite. The proton spectrum during the 27-day recurring event of October 18, 1964 is shown in Figure 3. The presence of low energy helium nuclei is also clearly indicated. A similar spectrum was found approximately 27 days later on 16-17 November 1964. For reference we have included the cosmic ray primary helium spectrum measured on the OGO-I satellite. Altogether five spectral samples have been obtained with the OGO-I particle telescope which show that these spectra of protons and helium are always present and similar at times of 27-day recurrences. These results along with our IMP-I and IMP-II observations, establish that helium nuclei are associated with the proton spectrum in these co-rotating regions.

#### IV. Continual Presence of Protons and Helium

Between these regions it would appear from Figure 1 that the low energy protons are absent; however, the later studies with the OGO-1 telescope show that this proton and helium component persists at a low intensity level at all times late in 1964. These fluxes would have appeared as only a small background in the IMP-1 counting rate. As an example we show in Figure 4 the spectra for protons and helium during a quiet time (15 December 1964). Measurements during other times between 27-day increases of intensity reveal spectra and intensity levels similar to those in Figure 4.

From measurements of 16 sets of proton and helium spectra distributed in time between October 15 and December 15, 1964 we always find these low energy components. The proton spectrum within a co-rotating region has an exponent  $\gamma \sim 3.5$ , whereas outside these regions the exponent rises to  $\gamma \sim 5$  or 6 and the intensity decreases. On the other hand, the helium spectrum inside or outside the 27-day recurring region has an exponent which varies only over the range  $\gamma \sim 2$  to 3. The data are also fitted reasonably well by an exponential form of spectra.

#### V. Discussion

The presence of a helium component which correlates in time with the changes in energy spectrum and flux levels of the proton component is convincing evidence that both components have the same origin. Are they of galactic or solar system origin? To test whether they have diffused in from the galaxy we point out that there was a factor of  $\sim 1.5$  increase in the lowest

energy helium flux of galactic origin which occurred near 1 December 1964 (see Figures 2 and 3, Fan, Gloeckler and Simpson, this conference). On the other hand, for particles of 1 to 30 Mev/nucleon there was no significant increase in average flux level between the quiet periods of October - November and the measurements in December (Figure 4). In addition, the persistent particle intensity structure co-rotating with the Sun would be difficult to maintain by particle diffusion from the galaxy.

As a more likely alternative, a crude physical picture based upon these preliminary results begins to emerge in which protons and helium nuclei may be accelerated continuously either (1) near the Sun at the "roots" of the enhanced magnetic field regions so as to preferentially stream outward along the co-rotating magnetic field structures, or (2) in the interplanetary medium within the co-rotating field structure, or in the region of its continual interaction with disordered magnetic fields beyond the orbit of Earth.

For either of the above alternatives the particles diffuse and are convected gradually throughout the inner solar system and escape to the galaxy. The observed intensity levels and changes in the exponents of the spectra for protons and helium as a function of time would, therefore, be determined by the relative strengths of the "source" and "sink". The source of accelerated particles may be sufficient to maintain a dynamic equilibrium of protons and helium nuclei within the inner solar system at this period of minimum solar activity. It will be important to learn whether particles



from this accelerating mechanism will attain higher energies as the solar cycle develops, and whether they could reach energies of order 100s Mev/nucleon to form a spectrum similar to that found by Vogt (1962) in 1961, around 80 to 300 Mev.

It is an interesting question why all co-rotating regions identified directly by magnetic field and plasma measurements in space, or indirectly by their modulation of cosmic rays, do not always contain enhanced fluxes of these protons and helium nuclei. (For example, see the B series in Figure 1.) Furthermore, the observed persistence of spatial structure of proton intensity discussed in Section II raises the possibility of proton streaming from a region where the magnetic "channel" connects with the Sun. These points may become arguments against acceleration in interplanetary space and in favor of solar acceleration.

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Figure Captions

- Figure 1      The interplanetary counting rate of protons of 20 Mev energy and some background from higher energy cosmic radiation is shown as a function of time. The main 27-day recurring series of co-rotating regions appears under A. An intermittent series appears under B. The shaded area for days 340-344 is called the "trailing" portion of the recurring region.
- Figure 2      Differential energy spectra of protons from the pulse height analyzer on IMP-I satellite.
- Figure 3      Differential proton and helium spectra during a 27-day-co-rotating region. The insert is a cross-section of the proton/helium telescope on the OGO-I satellite launched 4 September 1964. 1 and 2 refer to Au-Si solid state detectors; 3 is a scintillator cup which is in anticoincidence with 1 and 2. The energy loss in 1 is measured by a 128-channel pulse height analyzer.
- Figure 4      Differential proton and helium spectra during a "quiet" time.

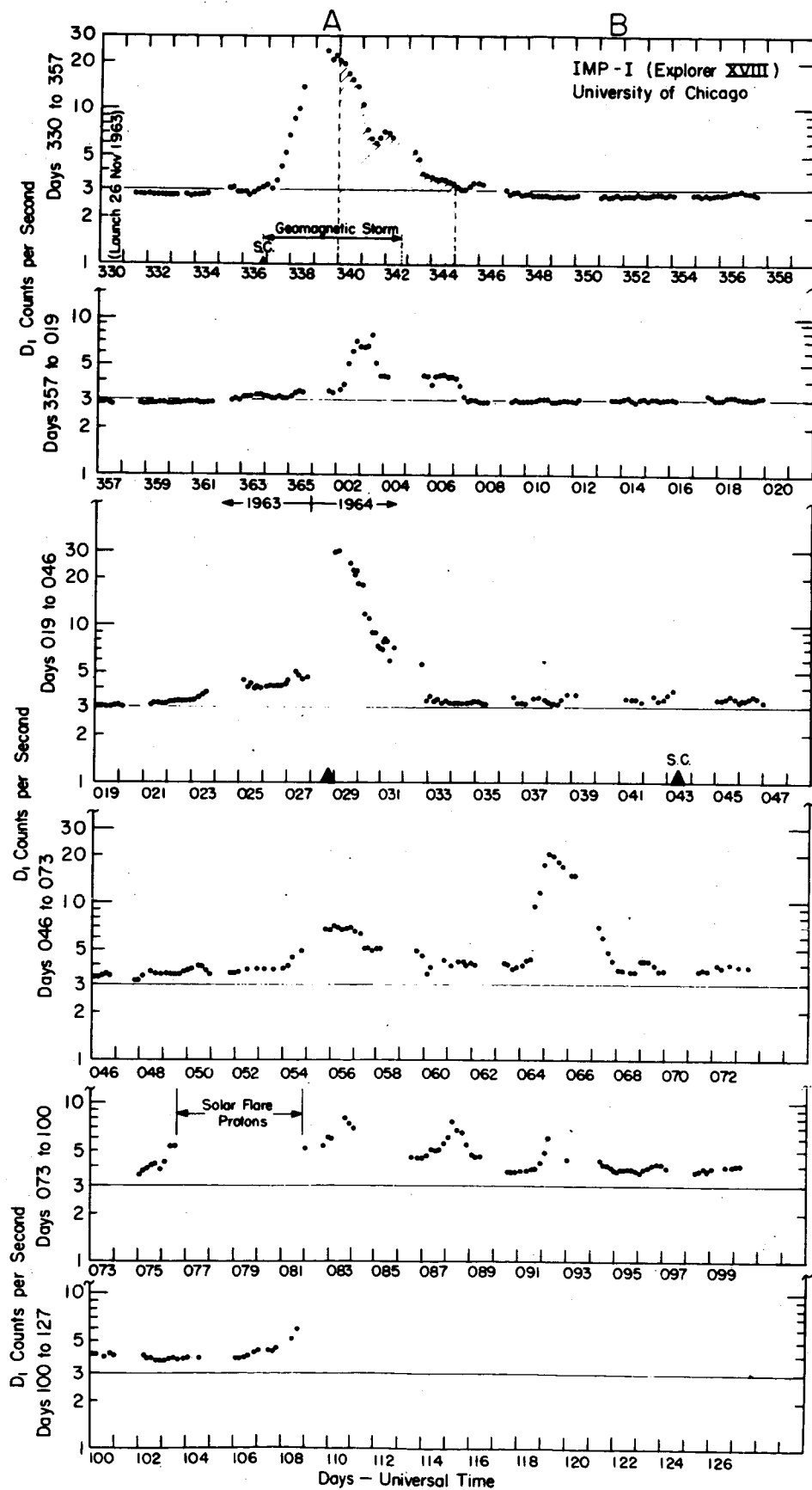


Fig. I

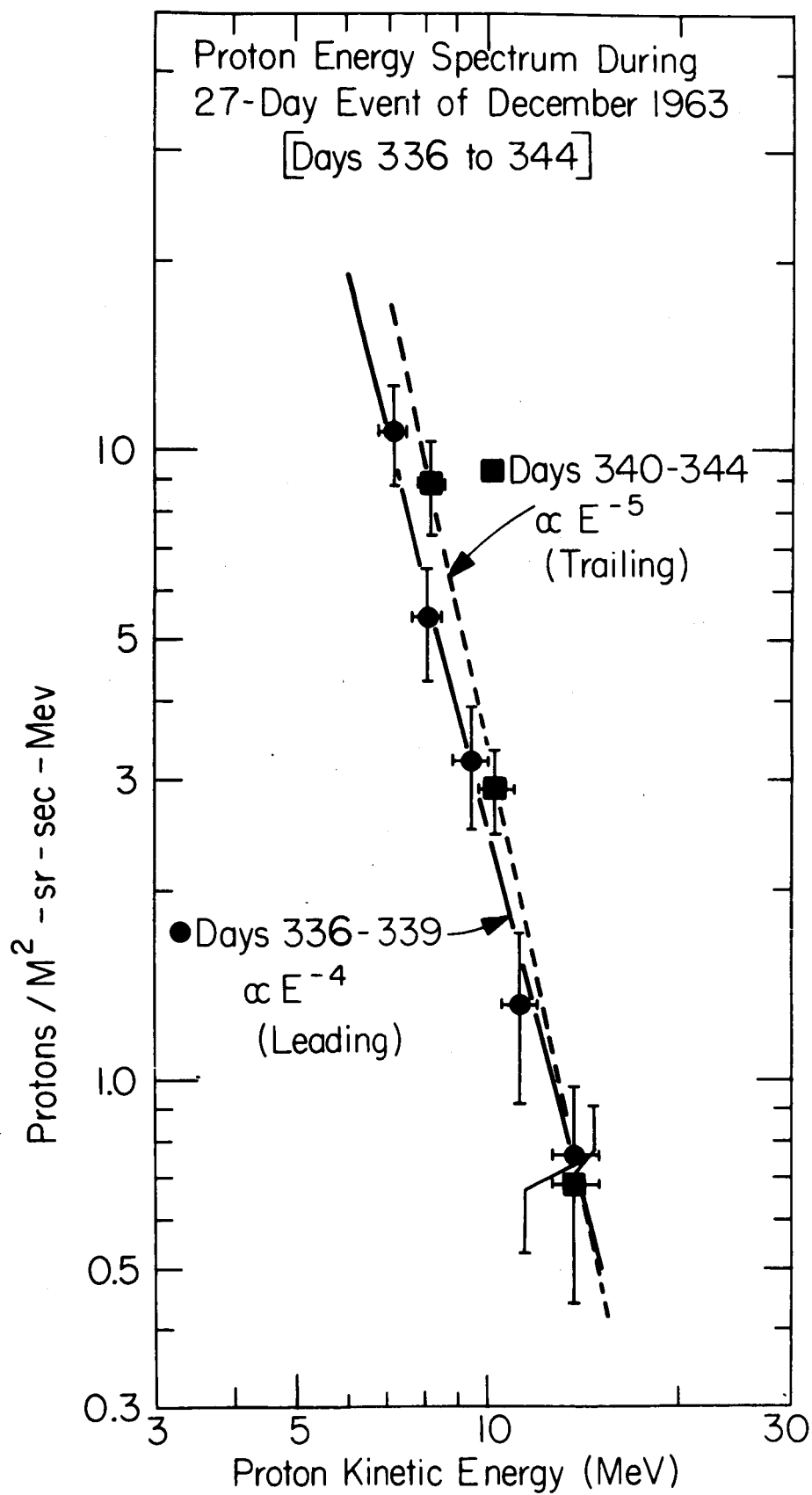


Fig. 2

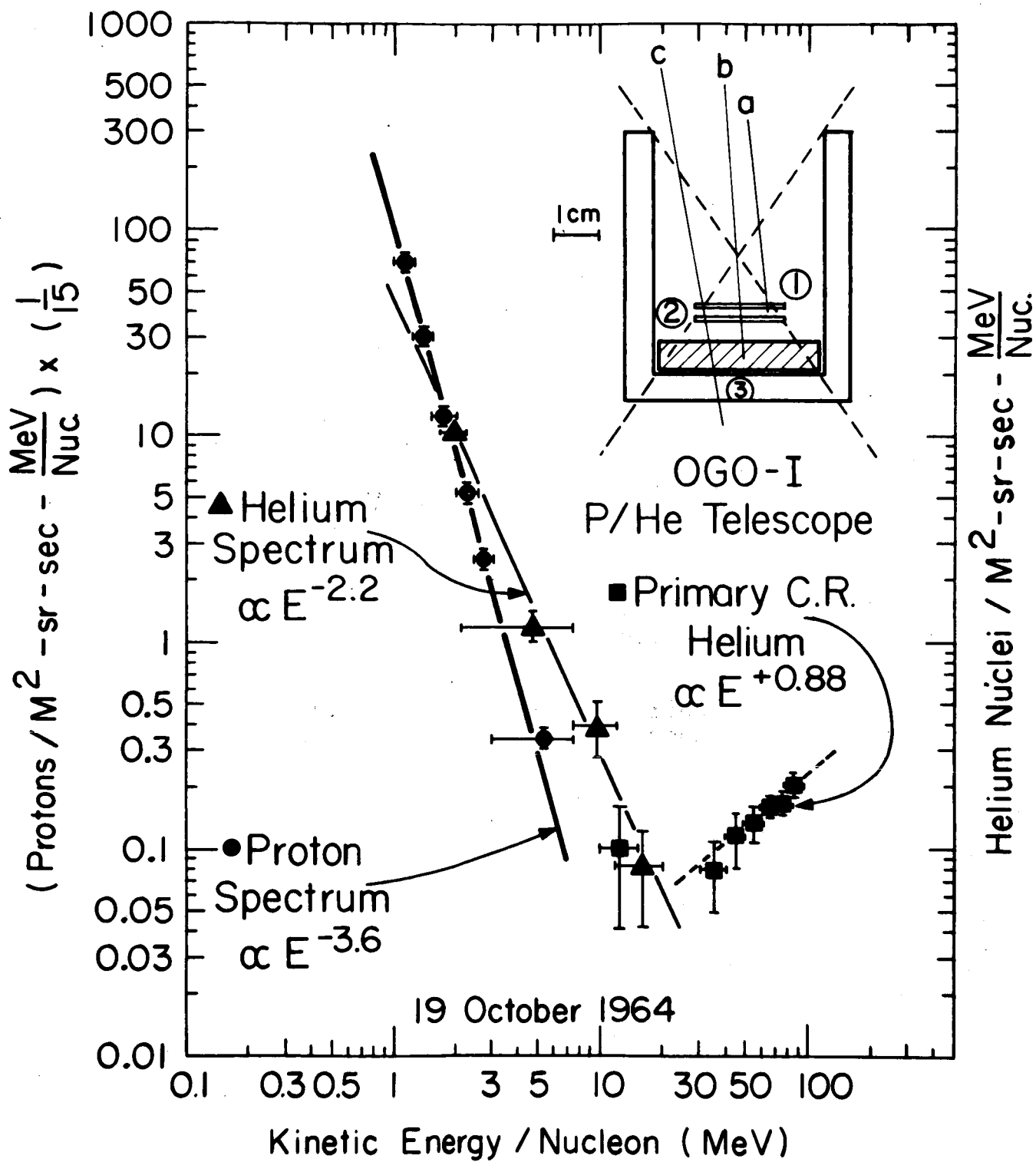


Fig. 3

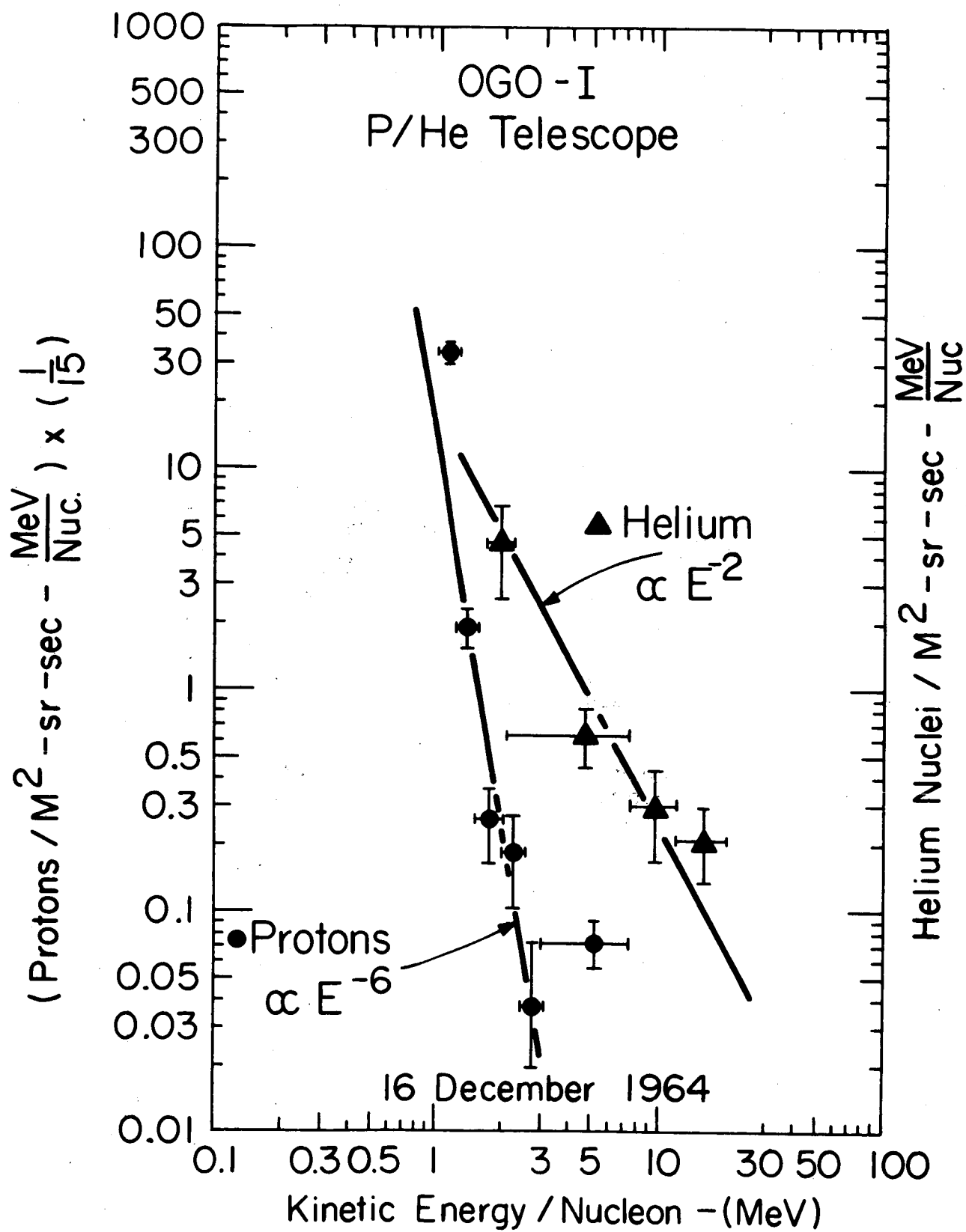


Fig. 4